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ORIGINALS ORIGINALARBEITEN

Influence of heat pressure steaming (HPS) on the mechanical and physical properties of common oak wood

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Abstract Common oak (*Quercus robur*) was thermally treated applying a heat pressure steaming procedure. Physical and mechanical properties of treated and untreated samples were investigated extensively. Swelling, water absorption, water vapour resistance, porosity and thermal conductivity were tested and the mechanical properties of tensile, bending and compression strength and of Young's modulus (static and dynamic) as well as Poisson's ratio and shear modulus were determined. The tests were carried out in the standard climate 20 °C and 65 % relative humidity and also in all three anatomical main directions: longitudinal, radial and tangential. The equilibrium moisture content at 20 °C and 65 % relative humidity for HPS (heat pressure steamed) oak (determined in adsorption test) was 6.7 % and for untreated oak 9.1 %. Swelling in longitudinal direction was not affected: a reduction of 17 and 10 % could be observed in radial and tangential direction, respectively. The porosity of the treated samples was 53.9 % in comparison to the untreated samples with 51.0 %. The thermal conductivity depending on the modification procedure changed only slightly which was related to the different densities of the samples. The water vapour resistance of the modified samples increases compared to the untreated samples. The values are double (dry-cup) respectively three times (wet-cup) higher than those of the reference samples. The elastic properties were not influenced by heat pressure steaming. The MOE does not show a significant change depending on the treatment. Bending and tensile strength of HPS oak decrease. In longitudinal direction, the tensile strength drops by 26 % and the bending strength by 25 %.

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Einfluss der Hitze-Druck-Dämpfung auf mechanische und physikalische Eigenschaften von Stieleiche

Zusammenfassung Stieleiche (*Quercus robur*) wurde durch eine Hitze-Druck-Dämpfung thermisch behandelt. Folgende physikalische Eigenschaften wurden analysiert: Quellung, Sorption, Wasserdampfwiderstand, Porosität und thermische Leitfähigkeit. Das mechanische Verhalten wurde durch die Parameter Zug-, Biege- und Druckfestigkeit bestimmt. Die E-Moduli wurden für die gleichen Belastungsarten bei statischer und dynamischer Beanspruchung ermittelt. Weiter erfolgte die Analyse der Querkontraktionszahlen sowie der Schubmoduli. Die Tests wurden im Normalklima bei 20 °C und 65 % relativer Luftfeuchte in allen drei anatomischen Richtungen longitudinal, radial und tangential ausgeführt. Durch die Hitze-Druck-Dämpfung wird die Ausgleichsfeuchte des Eichenholzes (ermittelt im Adsorptionsversuch) im oben genannten Normalklima von 9.1 % auf 6.7 % reduziert. Die Quellung in longitudinaler Richtung wird nicht beeinflusst, in radialer und tangentialer Richtung erfolgt eine Reduktion um 17 % bzw. 10 %. Die Porosität der behandelten Proben erhöht sich von 51 % auf 53.9 %. Die thermische Leitfähigkeit ändert sich nur geringfügig, was auch in Zusammenhang mit der Dichte der Proben steht. Der Wasserdampfdiffusionswiderstand der behandelten Proben steigt deutlich an, beim dry-cup Verfahren um das Doppelte und beim wet-cup Verfahren um das 3fache im Vergleich zu den unbehandelten Proben. Die elastischen Eigenschaften erfahren durch die Hitze-Druck-Dämpfung

keine Änderung. Die Biegefestigkeit wird um 25 % und die Zugfestigkeit um 26 % (jeweils in Faserlängsrichtung) reduziert.

1 Introduction

According to Gross (2011), thermally treated wood, mostly hardwood, is of national and international importance. Hardwood has been thermally tempered by various industrial methods. Essential for the customers and thus the attractiveness of the product is the characteristically dark colouring of treated wood. Esteves et al. (2008) studied interrelations between wood colour and partial degradation caused by thermal decomposition of hemicelluloses in the cell assembly. Similar darkening of a variety of timber can be achieved by steaming. The colour changes of pressure steamed oak wood has been rudimentarily described by Riehl et al. (2002) and in more detail by Dagbro et al. (2010).

For a long time, steaming processes have been recognized in the wood industry as a means to homogenize the colour of wood, or to prevent growth stresses. Works on this subject can be found in Kollmann (1951) and Vorreiter (1958).

In comparison to thermo treated wood, heat pressure steaming (HPS) results in a lower smell emission, and the strength is only slightly affected. The positive effects of Thermowood, such as increased durability and resistance to microorganisms, are not required for indoor applications. Compared to conventional thermal treatments of hardwood, steaming needs lower temperature regimes.

HPS hardwood products might constitute an economically and environmentally attractive and adequate alternative to Thermowood assortments for indoor use.

HPS wood lacks a detailed characterization regarding its mechanical and physical properties. Likewise, only a few studies on the properties along the principal axes are available for untreated oak wood. These characteristics are in high demand, in particular for modelling and numerical description of the material. Pressure steaming may also present an important possibility to increase the value of hardwood. In addition, the methodology is transferable to other species.

1.1 State of knowledge

Thermal treatment is the oldest, and nowadays the most commercialized, technology to modify wood. Tiemann (1942) reported on a study from 1915 where significant changes in the physical constitution of heat treated wood had been achieved. Among other factors, he described a reduction in moisture adsorption of heat-treated samples during a 4-h treatment at 150 °C.

The chemical changes in the macromolecular components of wood result in improved dimensional stability, reduction of hygroscopicity, reduced strengths and moduli, increased cracking behaviour and darker colour. These changes are directly related to the type of treatment as well as other process parameters. Hill (2006) lists the most important variables influencing the properties of thermally treated wood: temperature, duration of treatment, treatment atmosphere and wood species.

Depending on the temperature, wood loses mass when heated up. However, thermal degradation is a gradual process. The thermal stability of the wood components increases in the order of hemicelluloses (polyoses), cellulose and lignin. The boundaries of the decomposition are difficult to set because of an overlap of the different stages. In literature, different values for thermogram analyses of wood components can be found. Fengel and Wegener (2003) define five basic temperature ranges:

- 90 to 150 °C evaporation of bound water.
- 100 to 250 °C partial degradation of polyoses.
- 150 to 350 °C partial degradation of cellulose.
- 220 to 500 °C partial degradation of lignin.
- Above 500 °C pyrolysis (gasification) of wood (partial pyrolysis may start already at 280 °C).

2 Materials and methods

2.1 Test material

All test specimens for the determination of physical and mechanical properties were cut from logs of common oak (*Quercus robur*) from Switzerland with a mean normal density of 620–670 kg/m^3.

The treatment was executed using an industrial plant with a maximal package size of 6 × 1.2 × 1.5 m. Due to production reasons and in order to maintain a certain productivity the chamber was completely filled with wood during heat pressure steaming. The wood itself was predried in an industrial kiln down to moisture content (MC) of 8–12 %. Due to the industrial process and the drying volume in the kiln, the variation of the moisture content after drying (and prior to heat pressure steaming) could not be reduced further. The treatment process (Fig. 1) started with heating up the material from 20 to 120 °C, which takes 10 h. During this time, 5 l water/h was sprayed into the chamber to avoid serious surface cracking. After that, the temperature remained at 120 °C and the pressure was kept at 1.6–1.8 bar. Like in the heating up phase, 5 l water/h was sprayed into the chamber. The steaming phase lasted 50 h. In the last stage of 10 h, the wood was cooled down to 60 °C before the autoclave was opened. At this time, the

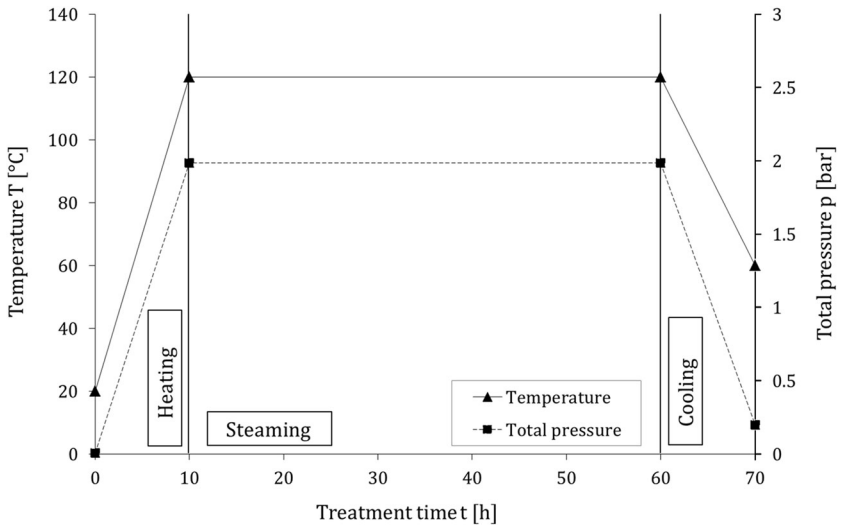

Fig. 1 Process scheme of a characteristic heat-pressure steaming process of wood with the three classical phases heating, steaming and cooling
Abb. 1 Verfahrensschema eines charakteristischen Hitze-Druck-Dämpfverfahrens von Holz mit den drei klassischen Phasen Aufheizen, Dämpfen und Abkühlen

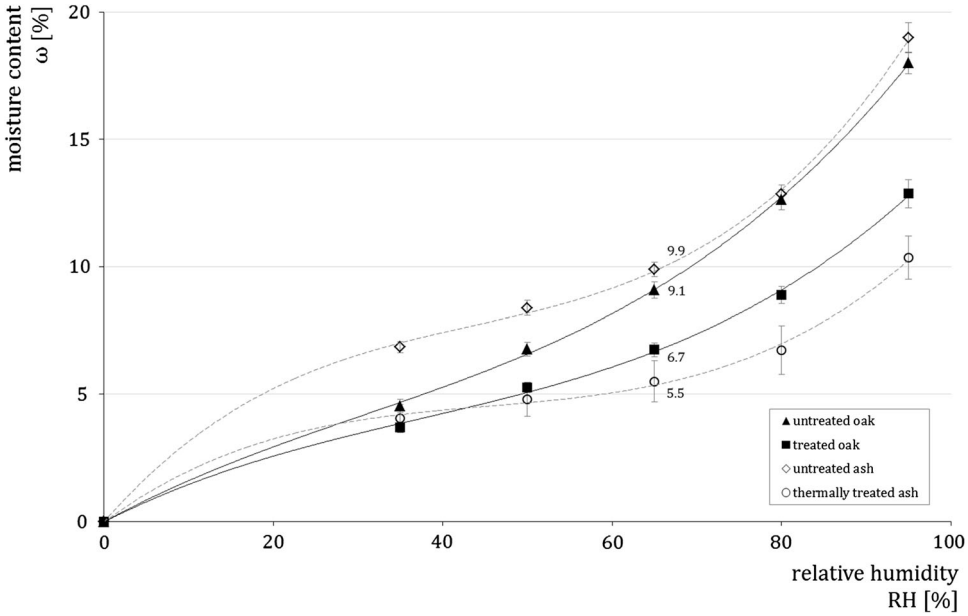

Fig. 2 Sorption isotherms of untreated and treated oak specimens compared with untreated and thermally treated ash samples (*dashed lines*) from previous measurements
Abb. 2 Sorptionsisothermen unbehandelter und behandelter Eichenproben im Vergleich mit unbehandelten und thermisch behandelten Eschenproben (gestrichelt) aus früheren Messungen

wood has an equilibrium moisture content of approximately 8 %. More detailed information on the process parameters can be found in Lorenz (2013).

2.2 Methods

To evaluate the modification process, the hygroscopic and mechanical behaviour of the treated oak were tested. The following properties were in the focus of the physical investigations: sorption isotherms, swelling, water vapour resistance, thermal conductivity, and porosity. The following mechanical properties were tested at 20 °C and 65 % relative humidity (RH): bending strength with static and dynamic modulus of elasticity (MOE), tensile strength in the three main directions [longitudinal (L), tangential (T), and radial (R)], compression strength in the three main directions, MOE and Poisson's ratio from tensile and compression tests, dynamic MOE and shear modulus (G) with different methods. The applied climate conditions result in a moisture content for the reference samples of 9.1 % and for the heat pressure steamed samples of 6.7 % (see Fig. 2).

For statistical evaluation, mean values and standard deviation were calculated for the different properties. To evaluate the influence of the treatment on the properties, the standard two sample *t* test was applied with a significance level of 5 %.

2.2.1 Determination of the physical properties

2.2.1.1 Swelling The swelling ratio (differential swelling) was determined in the L-, R- and T-directions for the

climates 20/35 and 20/93 (adsorption) according to DIN 52184:1979-05. 35 specimens sized 20 mm (R) × 20 mm (T) × 100 mm (L) were used for the L-direction and 35 specimens sized 50 mm (R) × 50 mm (T) × 10 mm (L) for the R- and T-directions.

2.2.1.2 Sorption The samples were placed in a climate chamber with a constant temperature of 20 °C. The relative humidity was increased in steps from 35, 50, 65 to 93 % until the probes were acclimatized to the corresponding equilibrium moisture content.

Finally the moisture content for each sample was determined according to DIN 52 183 (1977). The measurement was done on the same 35 samples used for the swelling analysis in L-direction.

2.2.1.3 Porosity The porosity, determined with the mercury intrusion porosimetry (MIP) method, only determines the percentage of open pores that are Hg-accessible. MIP was carried out with a combined instrument (Pascal 140 + 440, POROTEC) for measuring macro- and mesopores in the range 58,000–1.8 nm (described by Plötze and Niemz 2011). The cubic specimens, sized 4 mm, were conditioned at a climate of 20/65. Two samples per variant were measured.

2.2.1.4 Thermal conductivity Thermal conductivity was tested perpendicular to the grain on three solid wood boards (size: 500 × 500 × 20 mm) with the guarded hot plate apparatus λ-Meter EP500 (Lambda-Messtechnik GmbH, Dresden) according to DIN EN 12667 (2001). The specimens were conditioned at climates 20/35, 20/65, 20/95 and oven-dried. After each conditioning, thermal conductivity was measured at three temperatures (10, 20 and 30 °C) each with a temperature difference of 10 K between the hot and the cold plate and a surface pressure of 2500 N/m^2. The applied thermal conductivity at 10 °C was then determined by the evaluation software EP 500_PC 5.14 with a linear regression through the values at the three temperatures. Three samples per variant were analysed.

2.2.1.5 Water vapour resistance The water vapour resistance factor μ was determined according to DIN EN ISO 12572:2001 in the radial direction at dry (20 °C—65/0 % RH) and wet (20 °C—65/100 % RH) conditions. Ten specimens with a diameter of 140 mm and a thickness of 20 mm per climate and direction were tested. The diffusion coefficient D was calculated according to the following equation:

$$D = g \cdot \frac{d}{\Delta c}\,[m^2/s] \tag{1}$$

where d is sample thickness in mm and Δc difference of water concentration in kg/m^3.

$$\Delta c = 2 \cdot \left|u_{20/65} - u_x\right| \cdot \frac{m_{dtr}}{V}\,[kg/m^3] \tag{2}$$

$u_{20/65}$ Moisture content of the sample at 20 °C and 65 % RH
u_x Average moisture content of the sample during the test
m_{dtr} Dry mass of the sample in kg
V Volume of the sample in m^3

2.2.2 Determination of the mechanical properties

2.2.2.1 Bending strength, static and dynamic MOE Bending strength and static MOE were determined according to DIN 52186:1978 on 20 specimens sized 400 mm (L) x 20 mm (R) x 20 mm (T). Previously, sound velocity and eigenfrequency had been tested on the same specimens using an ultrasound device (BP-V, 50 kHz, Steinkamp, Bremen) and an impulse excitation tester (Grindosonic MK 5 'Industrial', Lemmens N. V., Belgium). Then, the dynamic MOE was calculated from sound velocity (c) and density (ρ) with the basic relation equation:

$$E = \rho \cdot c^2 \tag{3}$$

and from the eigenfrequency (first flexural mode) according to the method by Görlacher (1996):

$$E_f = \frac{4\pi^2 \cdot l^4 \cdot f^2 \cdot \rho}{m_n^4 \cdot i^2} \cdot \left(1 + \frac{i^2}{l^2} \cdot K_1\right)[N/mm^2] \tag{4}$$

l Length of the sample in mm
f Resonance frequency in s^{-1}
ρ Density in kg/m^3
i Radius of gyration in the direction of bending vibration
m_n, K_1 Constants of vibrations in N/mm^2

For the vibration of the first flexural mode:
$m_n = 500.6$ N/mm^2.
$K_1 = 49.48$ N/mm^2.

2.2.2.2 Tensile strength Tensile strength was determined parallel to the grain according to DIN 52188:1979. Dog-bone shaped specimens (Hering 2011) with a length of 95 mm (cross-sectional area: max. 28 × 28 mm, min. 14 × 14 mm) were used to measure the tensile strength perpendicular to the grain. Ten specimens per direction and climate (20 °C/65 % relative humidity) were tested.

2.2.2.3 Compression strength Compression strength parallel to the grain was determined according to DIN

52185:1976 and perpendicular to the grain according to DIN 52192:1979. Deviating from the norm, a reduced specimen size (15 × 15 × 45 mm) was employed. Ten specimens per direction and climate (20 °C/65 % relative humidity) were tested.

2.2.2.4 MOE and Poisson's ratio from tensile and compression tests MOE and Poisson's ratio were determined on the tensile and compression test specimens by means of a video image correlation system (Vic 2D, LIMESS Messtechnik & Software GmbH, Krefeld) for the determination of the longitudinal and transverse elongation. The method was described in detail by Keunecke (2008) and Hering (2011). The Poisson's ratio was determined according to:

$$\mu_{ij} = -\frac{\varepsilon_i}{\varepsilon_j} \quad (5)$$

where μ_{ij} is Poisson's ratio, ε_i the transverse elongation and ε_j the longitudinal elongation.

2.2.2.5 Dynamic MOE and shear modulus Dynamic MOE and shear modulus were determined on 20 cubic specimens with a side length of 10 mm by means of ultrasound. The tests were carried out using an Epoch XT device (Olympus NDT Inc., USA) with an Olympus A133S transducer (2.27 MHz) for longitudinal waves (determination of MOE) and a Staveley S-0104 transducer (1 MHz) for transverse waves (determination of G) and the coupling agent Ultragel II (Sonotech, USA). The MOE was determined according to Equation (3) and the shear modulus according to:

$$G_{ij} = c_{ij}^2 \cdot \rho \quad (6)$$

where c is the sound velocity and ρ the density. Thereby, as for the calculation of G from sound velocity, the directions of wave propagation (first index) and oscillation (second index) are exchangeable for an orthotropic material. The values of Gij and Gji were averaged. For more details see Keunecke (2008).

The static tests were carried out with a Zwick Z010 universal testing machine (Zwick GmbH & Co. KG, Ulm) for tension and compression perpendicular to the grain and a Zwick Z100 machine for tension, bending and compression parallel to the grain as well as shearing.

3 Results and discussion

In the following chapter, the physical and mechanical properties of HPS oak are presented. From a technical point of view, the effects of HPS range between classical steaming and thermal treatment. Accordingly, the physical properties differ from the two other modification procedures.

Classical steaming focuses on the stress relaxation and colour homogenization of the wood. The effect on swelling and shrinkage is rather small (Lohmann and Annies 1998). In comparison to this, thermal treatment causes significantly lower shrinkage and swelling behaviour depending on the

Table 1 Reference values of selected physical and mechanical properties of untreated oak

Tab. 1 Literaturwerte zu verschiedenen ausgewählten Eigenschaften der Eiche

Properties	Values	Sources
Normal density [kg/m^3]	390…650…930	1
	420…690…960	2
Porosity [%]	49.1	6
Thermal conductivity λ [W/mK]	0.11…0.17	1
	0.13…0.20	3
Swelling		
α_l (longitudinal) [%]	0.3…0.6	4
α_t (tangential) [%]	7.8…10.0	3
α_r (radial) [%]	4.0…4.6	3
Diff. swelling		
q_t (tang.) [%/ %]	0.28…0.35	5
q_r (rad.) [%/ %]	0.15…0.22	5
Impact bending strength w [kJ/mm^2]	10…60…160	1
MOE (bending) E_b [N/mm^2]	10,000…11,700…13,200	1
	10,500…14,500	5
MOE (compressive)		
E_c ∥ [N/mm^2]	11,800	7
E_c ⊥ [N/mm^2]	1,030…2,050	7
Flexural strength σ_f [N/mm^2]	74…88…105	1
	60…94…100	4
	86…108	5
Compressive strength		
σ_c ∥ [N/mm^2]	54…61…67	1
	41…55…59	4
σ_c ⊥ [N/mm^2]	8.5…11	7
Tensile strength		
σ_t ∥ [N/mm^2]	50…90…180	1
σ_t ⊥ [N/mm^2]	2.6…4.0…9.6	1
Shear modulus		
G_{lr} (long./rad.) [N/mm^2]	1,150	4
G_{lt} (long./tang.) [N/mm^2]	800	4
G_{rt} (rad./tang.) [N/mm^2]	400	4
Poisson's ratio μ [−]	lr…0.32/lt…0.50	4
	rl…0.12/rt…0.66	
	tl…0.085/tr…0.30	
Brinell hardness	17…23…28	3
HB ⊥ [N/mm^2]	23…42	5

Sources: 1 Kollmann (1951), 2 Vorreiter (1949), 3 Wagenführ (1996), 4 Niemz (1993), 5 Sell (1997), 6 Plötze and Niemz (2011), 7 Pozgaj et al. (1997)

process parameter. Furthermore, a temperature related decrease of all mechanical parameters and of the equilibrium moisture content was determined. The resistance of wood to destroying fungi increases with increasing process temperature and duration (Hill 2006).To better assess the HPS treatment, selected reference values of untreated oak with their corresponding sources are shown in Table 1.

3.1 Physical properties

3.1.1 Swelling

The modification process affects the swelling properties in the anatomical directions (Table 2) in a different way. No influence can be observed in the L direction at 0.02 %/%(Δu). However, the degree of differential swelling of the treated samples in the R and T directions are 17 and 10 %, respectively, less than that of untreated samples. The observed effect is obviously related to the reduction of the equilibrium MC.

Table 2 Differential swelling degree of the wood, mean value and standard deviation (sd)
Tab. 2 Differentielles Quellverhalten von unbehandeltem und behandeltem Eichenholz, Mittelwert und Standardabweichung (sd)

Diff. swelling degree q		Untreated	Treated
q_l [%/ %($\Delta\omega$)] (longitudinal)		0.020	0.021
	sd	0.005	0.004
q_r [%/ %($\Delta\omega$)] (radial)		0.18	0.15
	sd	0.03	0.02
q_t [%/ %($\Delta\omega$)] (tangential)		0.29	0.26
	sd	0.03	0.04

3.1.2 Sorption isotherms

The equilibrium MC of the treated wood is lower than that of the untreated wood (Fig. 3). Thus, it is lower than in conventional steaming, where no or only a slight change was observed. The MCs are between untreated and thermally treated ash, which was used as reference (since oak is usually not heat-treated). This can be explained by the relatively low process temperature of 120 °C (Schneider and Rusche 1973). During treatments at low temperatures, the hemicelluloses only slightly degrade and thus the influence on the sorption behaviour is rather small. Based on current literature, the relationships between thermal modification and changes in physical properties were comprehensively described by Hill (2006).

3.1.3 Porosity

The results of the measurements of the porosity are shown in Table 3 and Fig. 3. The porosity of untreated oak, given

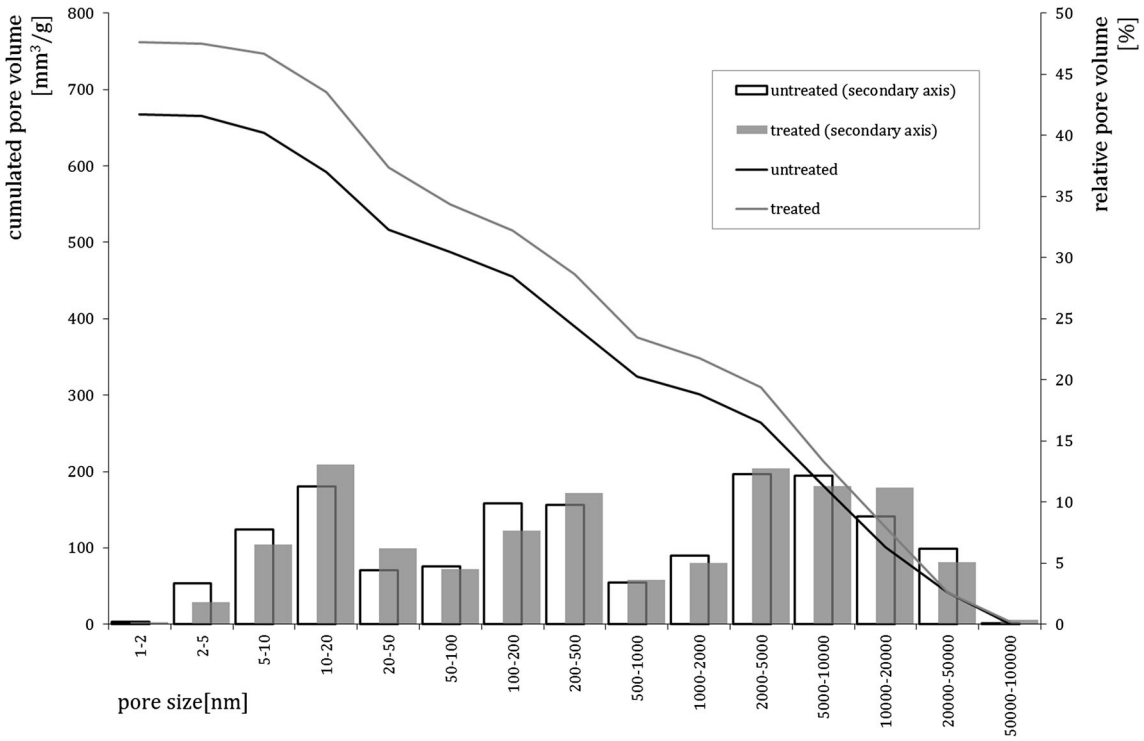

Fig. 3 Pore size distribution of untreated (*black*) and treated (*grey*) oak wood
Abb. 3 Porengrössenverteilung entsprechend den Behandlungsarten, unbehandelt (schwarz) und behandelt (grau)

Table 3 Results of porosity for untreated and treated oak wood
Tab. 3 Ergebnisse der Porositätsmessung für unbehandeltes und behandeltes Eichenholz

	Untreated	Treated
Density ρ (kg/m^3)	764	708
Bulk density ρ_s (kg/m^3)	1,557	1,537
Specific surface (m^2/g)	63.1	68.4
porosity *MIP* (%)	51.0	53.9
$n = \left[1 - \left(\frac{\rho}{\rho_s}\right)\right] * 100$		

by the ratio between normal and bulk density, is 51 % and corresponds to a specific surface area of 63.1 m^2/g. Compared to literature (49.1 %, Plötze and Niemz 2011), the untreated samples provide slightly higher characteristic values for porosity. This difference is directly related to the higher density of the specimens. The test with treated samples results in a porosity of 53.9 % and a specific surface area of 68.4 m^2/g. Logically, higher specific surface area is related to higher porosity. The porosity of the treated samples is around 5.7 % higher than that of the untreated samples. This value supports the observed changes in cell structure under the influence of temperature, particularly the decrease in cell wall thickness.

The increased porosity and the pore volume of the treated samples mainly occur within the pore size ranges of 10–20, 20–50 and 10,000–20,000 nm, although it is difficult to determine a systematic change. The pore size distributions of the compared treatment types are too similar.

3.1.4 Thermal conductivity

The thermal conductivity of the HPS wood is slightly higher than that of untreated wood (Table 4). This could be related to the higher density of the treated samples. Considering the reduced equilibrium MC of the treated samples, the difference would be even higher. The thermal conductivity also increases with increasing density and MC (Kollmann 1951, Niemz 1993).

3.1.5 Water vapour resistance

The examination results of the diffusion behaviour (Table 5) show that HPS significantly increases the vapour diffusion resistance, or rather decreases the diffusion coefficient. Furthermore, the known varieties between dry- and wet-cup measurements become evident. In this case, the density differences between untreated and treated specimens are small. Obviously, the changes in the cell structure and the lower MC affect the results. Similar dependencies can be determined for thermally treated wood (Krackler et al. 2011), which increased vapour resistance due to the chemical changes that occur as result of the treatment.

The vapour diffusion resistance of HPS wood in dry-cup is 421.8 compared to 193 (untreated): more than double the value, whereas the values of treated samples in wet-cup (137) exceed those of the untreated (39.7) by more than threefold.

These differences between the two types of test are remarkable. Dry-cup delivers consistently higher values. This phenomenon was mainly expected due to the different wood MC during the measurements (Sonderegger 2011).

3.2 Mechanical properties

In the following, the results of the mechanical properties corresponding to a climate of 20 °C and 65 % RH are presented. The reduction of the equilibrium MC due to the treatment is not considered. All tests were executed after conditioning the samples in the same standard climate (20 °C/65 % RH). The mean values between the treated and untreated samples were compared using the t-Test. The values in italics in Tables 6–9 indicate a significant difference corresponding to 95 % probability.

3.2.1 Elasto-mechanical properties

Table 6 shows the

results from the static compression and tensile tests in the main axes L, R and T as well as the MOE in the L direction during bending stress and transmission using BP-V in the L direction. Table 7 presents the Poisson's ratio.

The results can be summarized as follows:

- The MOE shows no essential distinction between HPS and untreated oak.
- In the main axes, the orthotropic behaviour is obvious—R moduli are significantly higher than T.

Table 4 Results and comparison with thermal conductivity across the grain of untreated and treated specimens
Tab. 4 Ergebnisübersicht zur Wärmeleitfähigkeit der Behandlungsarten unbehandelt und behandelt quer zur Faserrichtung

Climate (°C/ %RH)	Temperature T (°C)	Untreated			Treated		
		Moisture content ω (%)	Density ρ (kg/m^3)	Thermal conductivity λ (W/m*K)	Moisture content ω (%)	Density ρ (kg/m^3)	Thermal conductivity λ (W/m*K)
20/65	10	10.1	617	0.130	7.1	656	0.132

Table 5 Results and comparison to water vapour permeability of untreated and treated wood in radial diffusion direction; values in italics indicate a significant difference between the mean values with probability of 95 %

Tab. 5 Wasserdampfdurchlässigkeit der Behandlungsarten unbehandelt und behandelt in radialer Diffusionsrichtung; kursiv gedruckte werte enthalten jene Mittelwerte, welche sich mit einer Wahrscheinlichkeit von 95 % unterscheiden

		Density ρ (kg/m^3)	Moisture content ω (%)	Diffusion coefficient D (m^2/s)	Diffusion resistance μ (−)
Untreated					
Dry-cup (65/0 %RH)		619	8.1	6.95E−13	*193.0*
	sd			1.41E−13	39.6
Wet-cup (100/65 %RH)		627	18.1	5.02E−13	*39.7*
	sd			1.32E−13	9.3
Treated					
Dry-cup (65/0 %RH)		611	5.8	4.42E−13	*421.8*
	sd			1.15E−13	114.2
Wet-cup (100/65 %RH)		611	13.3	1.99E−13	*137.1*
	sd			5.14E−14	42.39

– The following relationship is revealed:
– compressive: R: T: L = 1:1.4:20–23.
– tensile: R: T: L = 1:1.7–1.8:12–13.
– The influence of steaming is negligible in comparison to the scattering of the characteristic values.
– The elastic characteristics of the compression tests vary considerably, probably due to the fibre angle and an inconstant strain flow inside the wood.
– Bending moduli (MOE) are approximately in the same range as tensile moduli, and compressive moduli are about 30 % higher.
– The various dynamic measurements show clear differences: ultrasound values at high frequency (Epoch, 2.27 MHz) are significantly higher than during the static tests. Eigenfrequency values are, however, similar to static test results, which corresponds to previous experiences by Keunecke (2008). Particularly large variations are revealed in measurements with Epoch in the fibre direction. At high frequencies, and thus low wavelengths, exclusion of the transversal contraction in calculating the MOE is relevant. If the Poisson's ratio is not considered, then the calculated MOE are almost 100 % higher than during the static tests. Including the

Table 6 Results and comparison to the elastic behaviour of untreated and treated oak wood in all anatomical directions, measured with various static and dynamic methods under standard climate conditions 20/65; values in italics indicate a significant difference between the mean values with probability of 95 %

Tab. 6 Ergebnisübersicht zum elastischen Verhalten von unbehandeltem und behandeltem Eichenholz in den drei holzanatomischen Richtungen bei verschiedenen statischen und dynamischen Messmethoden, gemessen bei Normalklima 20 °C und 65 %rLf; kursiv gedruckte werte enthalten jene Mittelwerte, welche sich mit einer Wahrscheinlichkeit von 95 % unterscheiden

Type of MOE or measuring		Untreated			Treated		
		Radial	Tang.	Long.	Radial	Tang.	Long.
Static							
Bending E_b in N/mm^2 (density in kg/m^3)				10,766 (641)			10,982 (655)
	sd			2,254			2,406
Moisture content ω (%)				10.8			7.2
Compressive E_c in N/mm^2 (density in kg/m^3)		*848 (637)*	617 (637)	*13,988 (637)*	*906 (613)*	654 (613)	*13,238 (613)*
	sd	54	102	5,982	92	113	5,589
Moisture content ω (%)		10.8	10.7	10.7	8.0	7.5	7.4
Tensile E_t in N/mm^2 (density in kg/m^3)		*1,348 (643)*	*810 (643)*	*9,508 (643)*	*1,659 (622)*	*911 (622)*	*11,886 (622)*
	sd	312	135	2,316	332	110	2,366
Moisture content ω (%)		11.0	11.1	11.1	8.1	7.8	7.8
Dynamic							
Eigenfrequency E_f in N/mm^2 (density in kg/m^3)				9,120 (641)			9,243 (665)
	sd			1,907			2,152
Moisture content ω (%)				10.8			7.2
Ultrasound BP-V E_{BPV} in N/mm^2 (density in kg/m^3)				13,851 (641)			14,062 (665)
	sd			2,630			2,839
Moisture content ω (%)				10.8			7.2
Ultrasound Epoch XT E_{XT} in N/mm^2 (density in kg/m^3)		*4,025 (680)*	2,535 (680)	17,281 (680)	*4,192 (613)*	2,605 (613)	14,333 (613)
	sd	341	315	4,808	644	671	3,596
Moisture content ω [%]		10.7	10.7	10.7	6.5	6.5	6.5

Table 7 Results and comparison to Poisson's ratio of untreated and treated oak wood in all six directions, measured with compressive and tensile loads under standard climate conditions 20/65 (first index = direction of load, second index = direction of contraction)
Tab. 7 Ergebnisübersicht der Poissonschen Konstanten von unbehandeltem und behandeltem Eichenholz in den sechs massgebenden Richtungen, gemessen unter Druck- und Zugbelastung bei Normklima (20 °C/65 % rLf), erster Index Richtung der Lasteinwirkung, zweiter Index Richtung der Kontraktion

Type of load		Untreated						Treated					
Compressive		μ_c (lr)	μ_c (lt)	μ_c (rl)	μ_c (rt)	μ_c (tl)	μ_c (tr)	μ_c (lr)	μ_c (lt)	μ_c (rl)	μ_c (rt)	μ_c (tl)	μ_c (tr)
		0.30	0.41	0.08	0.62	0.04	0.35	0.27	0.45	0.04	0.54	0.06	0.35
	sd	0.13	0.11	0.04	0.03	0.03	0.02	0.08	0.06	0.01	0.10	0.02	0.03
Tensile		μ_t (lr)	μ_t (lt)	μ_t (rl)	μ_t (rt)	μ_t (tl)	μ_t (tr)	μ_t (lr)	μ_t (lt)	μ_t (rl)	μ_t (rt)	μ_t (tl)	μ_t (tr)
		0.30	0.27	0.11	0.63	0.06	0.37	0.24	0.23	0.25	0.67	0.07	0.37
	sd	0.09	0.11	0.05	0.05	0.01	0.05	0.05	0.10	0.06	0.03	0.02	0.04

Table 8 Results of the shear modulus of untreated and treated oak wood in sonic directions longitudinal-radial (lr), longitudinal-tangential (lt) and radial-tangential (rt), dynamically measured by ultrasound analysis under standard climate conditions 20/65, values in italics indicate a significant difference between the mean values with probability of 95 %
Tab. 8 Ergebnisübersicht zum Schubmodul von unbehandeltem und behandeltem Eichenholz in den Schallrichtungen longitudinal-radial (lr), longitudinal-tangential (lt) und radial-tangential (rt), dynamisch bestimmt mittels Ultraschallanalyse mit Epoch XT gemessen bei Normalklima 20 °C und 65 %rLf, kursiv gedruckte werte enthalten jene Mittelwerte, welche sich mit einer Wahrscheinlichkeit von 95 % unterscheiden

Dynamic		Untreated			Treated		
		lr	lt	rt	lr	lt	rt
Epoch XT G_{XT} in N/mm^2		1,596	1,188	*460*	1,570	1,152	*369*
	sd	179	199	93	270	183	60
Moisture content ω (%)		10.7	10.7	10.7	6.5	6.5	6.5

transversal contraction, the values can be converted (Ozyhar et al. 2013) and more convenient results may be obtained. However, shear moduli are in the expected range.

3.2.2 *Poisson's ratio*

Table 7 shows the values for the Poisson's ratio. Regarding the natural variability of wood, the values differ only slightly between compressive and tensile loads and correspond well with literature (Pozgaj et al. 1997). The influence of steaming is negligible.

The shear moduli (Table 8), measured by transversal waves, correspond to literature values (Keunecke 2008, DIN 68364:1979). Influence of HPS could not be proven.

3.2.3 *Strength properties*

Regarding the strength properties, a clear differentiation in the three main axes is visible (Table 9).

Bending and tensile strength in the fibre direction drop significantly as result of HPS. The compressive strength seems not be affected. Differences between R and T directions are relatively low. The tensile strength is higher

Table 9 Results and comparison to strength properties of untreated and treated oak wood in all anatomical directions under standard climate conditions 20/65; values in italics indicate a significant difference between the mean values with probability of 95 %
Tab. 9 Ergebnisübersicht zur Festigkeit von unbehandeltem und behandeltem Eichenholz in den drei holzanatomischen Richtungen, gemessen bei Normklima 20 °C und 65 %rL; kursiv gedruckte werte enthalten jene Mittelwerte, welche sich mit einer Wahrscheinlichkeit von 95 % unterscheiden

		Untreated			Treated		
Bending strength σ_f in N/mm^2		*93.7*			*70.1*		
	sd	20.3			24.7		
Moisture content ω (%)		10.8			7.2		
		Radial	Tang.	Long.	Radial	Tang.	Long.
Compressive strength σ_c in N/mm^2		10.6	9.0	47.9	10.5	8.8	532
	sd	1.0	1.8	6.7	1.4	2.0	9.3
Moisture content ω (%)		10.8	10.7	10.7	8.0	7.5	7.4
tensile Strength σ_t in N/mm^2		*6.0*	*7.8*	*72.9*	*4.5*	*4.8*	*53.9*
	sd	0.9	1.4	19.2	0.9	0.9	24.0
Moisture content ω (%)		11.0	11.1	11.1	8.1	7.9	7.8

in the T direction than in the R direction, where the compressive strength delivers higher values.

In the L direction, as well as across the fibre, the treatment does not affect compressive strength. The differences in tensile strength between the R and T directions are significant. In the R direction, the tensile strength decreases by 15 %, and in the T direction, it reduces by almost 40 %.

The loss of strength under tensile load is related to the treatment temperatures. Similar results were obtained for thermally treated wood by Bekhta and Niemz (2003). A summary of the influence of thermal treatment on the mechanical properties of wood can be found in Hill (2006).

4 Conclusion

In this work, a broad database of HPS oak is provided. At the moment, data for this particular modification process is not available. As expected, the sorption behaviour of the treated samples decreases, which leads to a reduction in swelling and shrinking. The inner specific surface of the modified wood increases and consequently the porosity increases as well. Further, the water vapour diffusion is affected considerably by HPS. As result of the change in the chemical composition, the treated samples show significantly higher values for the wet- and dry-cup tests than untreated probes. The analysed modification process does not affect the elastic properties. In contrast, a clear decrease in bending and tensile strength is observed.

The presented database provides a good basis for evaluating the modification process. Further studies are necessary to describe the mechano-sorptive and plastic behaviour of HPS wood. For commercial application, the colour change and stability as well as the emission of VOCs are of major importance. Corresponding investigations are in progress.

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References

Bekhta P, Niemz P (2003) Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood. Holzforschung 57:539–546

Dagbro O, Torniainen O, Morén T (2010) Colour responses from wood, thermally modified in superheated steam and pressurized steam atmospheres. Wood Mat Sci Eng 5:211–219

DIN 52192 (1979) Prüfung von Holz, Druckversuch quer zur Faserrichtung, Deutsches Institut für Normung, Berlin

DIN 52 185 (1976) Prüfung von Holz, Bestimmung der Druckfestigkeit parallel zur Faser, Deutsches Institut für Normung, Berlin

DIN 52 183 (1977) Prüfung von Holz. Bestimmung des Feuchtigkeitsgehaltes. Nov. 1977

DIN 52 186 (1978) Prüfung von Holz, Biegeversuch, Deutsches Institut für Normung, Berlin

DIN 52 184 (1979) Prüfung von Holz, Bestimmung der Quellung und Schwindung, Deutsches Institut für Normung, Berlin

DIN 52 188 (1979) Prüfung von Holz, Bestimmung der Zugfestigkeit parallel zur Faser, Deutsches Institut für Normung, Berlin

DIN 68 364 (1979) Kennwerte von Holzarten, Festigkeit, Elastizität und Resistenz, Deutsches Institut für Normung, Berlin

DIN EN 12 667 (2001) Wärmetechnisches Verhalten von Baustoffen und Bauprodukten: Produkte mit hohem und mittlerem Wärmedurchlasswiderstand, Bestimmung des Wärmedurchlasswiderstandes nach dem Verfahren mit dem Plattengerät und dem Wärmestrommessplatten-Gerät, Deutsches Institut für Normung, Berlin

DIN EN ISO 12 572 (2001) Wärme- und feuchtetechnisches Verhalten von Baustoffen und Bauprodukten, Bestimmung der Wasserdampfdurchlässigkeit, Deutsches Institut für Normung, Berlin

Esteves B, Velez Marques A, Domingos I, Pereira H (2008) Heat-induced colour changes of pine (Pinus pinaster) and eucalypt (Eucalyptus globulus) wood. Wood Sci Technol 42:369–384

Fengel D, Wegener G (2003) Wood Chemistry, Ultrastructure, Reactions. Kessel Verlag, Remagen

Görlacher R (1996) Hölzerne Tragwerke Untersuchen und Beurteilen, Empfehlungen für die Praxis, Sonderforschungsbereich 315: Konstruktionen. Werkstoffe, Karlsruhe

Gross D (2011) Jahrbuch Wald und Holz. Bundesamt für Umwelt BAFU, Bern

Hering S (2011) Charakterisierung und Modellierung der Materialeigenschaften von Rotbuchenholz zur Simulation von Holzverklebungen, PhD thesis, ETH Zürich

Hill CAS (2006) Wood modification chemical, thermal and other processes, Wiley series in renewable resources. Wiley, Chichester

Keunecke D (2008) Elasto-mechanical characterisation of yew and spruce wood with regard to structure-property relationships, ETH Zürich

Kollmann F (1951) Technologie des Holzes und der Holzwerkstoffe. Springer, Berlin

Krackler V, Camathias U, Amman S, Niemz P (2011) Untersuchungen zum Feuchteverhalten und zur Porosität von thermisch modifiziertem Holz. Bauphysik 33:374–381

Lohmann U, Annies T (1998) Holz-Handbuch. DRW, Leinfelden-Echterdingen

Lorenz T (2013) Physikalisch-mechanische Eigenschaften von im Autoklaven gedämpftem Laubholz. Bachelorarbeit, Berner Fachhochschule

Niemz P (1993) Physik des Holzes und der Holzwerkstoffe. DRW, Leinfelden-Echterdingen

Ozyhar T, Hering S, Niemz P (2013) Moisture-dependent orthotropic tensions-compression asymmetrie of wood. Holzforschung 67:395–404

Plötze M, Niemz P (2011) Porosity and pore size distribution of different wood types as determined by mercury intrusion porosimetry. Eur J Wood Prod 69:649–657

Pozgaj A, Chovanec D, Kurjatko S, Babiak M (1997) *Struktura a vlastnosti Dreva* (Structure and porperties of wood) Bratislava: Priroda a.s., 2nd edition

Riehl T, Welling J, Frühwald A (2002) Druckdämpfen von Schnittholz, Arbeitsbericht 2002/01: Institut für Holzphysik. Bundesforschungsanstalt für Forst- und Holzwirtschaft, Hamburg

Schneider A, Rusche H (1973) Sorptionsverhalten von Buchen- und Fichtenholz nach Wärmeeinwirkung in Luft und Vakuum. Holz Roh Werkst 31:313–319

Sell J (1997) Eigenschaften und Kenngrössen von Holzarten. Baufachverlag, Bern

Sonderegger WU (2011) Experimental and theoretical investigations on the heat and water transport in wood and wood-based materials. ETH, Zürich

Tiemann HD (1942) Wood technology constitution, properties and uses. Pitman, New York

Vorreiter L (1949) Holztechnologisches Handbuch Band I: Allgemeines, Holzkunde, Holzschutz und Holzvergütung, Georg Fromme & Co, Wien

Vorreiter L (1958) Holztechnologisches Handbuch Band II: System Holz-Wasser-Wärme, Holztrocknung, Dämpfen und Kochen, Spanlose Holzverformung, Georg Fromme & Co., Wien

Wagenführ R (1996) Holzatlas. Fachbuchverlag, Leipzig